Test Results for the Automated Rendezvous and Capture System

Craig Cruzen, Richard Dabney and James Lomas †

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Abstract

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† Aerospace Engineers, NASA George C. Marshall Space Flight Center, Huntsville, AL 35812

Correspondence to Craig Cruzen: Phone 256-544-8658 email: craig.cruzen@msfc.nasa.gov
Correspondence to Richard Dabney: Phone 256-544-2586 email: richard.dabney@msfc.nasa.gov
Correspondence to James Lomas: Phone 256-544-8305 email: james.lomas@msfc.nasa.gov

TEST RESULTS FOR THE AUTOMATED RENDEZVOUS AND CAPTURE SYSTEM

Craig A. Cruzen, Richard W. Dabney and James J. Lomas[†]

The Automated Rendezvous and Capture (AR&C) system was designed and tested at NASA's Marshall Space Flight Center (MSFC) to demonstrate technologies and mission strategies for automated rendezvous and docking of spacecraft in Earth orbit. The system incorporates some of the latest innovations in Global Positioning System (GPS) space navigation, laser sensor technologies and automated mission sequencing algorithms. The system's initial design and integration was completed in 1998 and underwent testing in 1999. This paper describes the major components of the AR&C system and presents results from the official system tests performed in MSFC's Flight Robotics Laboratory with digital simulations and hardware in the loop tests. The results show that the AR&C system can safely and reliably perform automated rendezvous and docking missions in the absence of system failures with 100 percent success. When system failures were included, the system used its automated collision avoidance logic to recover in a safe manner. The primary objective of the AR&C project is to prove that by designing a safe and robust automated system, mission operations cost can be reduced by decreasing the personnel required for mission design, preflight planning and training required for crewed rendezvous and docking missions.

INTRODUCTION

Since the 1960's, the National Aeronautics and Space Administration (NASA) has been performing rendezvous and docking missions between two spacecraft. Recent examples of how this has become commonplace in space operations include the servicing of the Hubble Space Telescope, Space Shuttle/MIR dockings and International Space Station (ISS) construction missions. One common thread that remains between the current NASA mission philosophy and the very first Gemini docking mission is that at least one of these spacecraft has always been piloted by astronauts and supported by a virtual army of ground personnel. When the Russian space program developed an automated docking system, it was seen as a way to decrease costs of space flight by reducing the amount of support personnel required for docking operations. However, the near fatal accident that occurred when a docking attempt ended in collision between an unmanned, tele-operated controlled Soyuz supply ship and MIR showed that a great deal of safety and redundancy must be designed into any docking system. NASA has several missions on the horizon that will require an Automated Rendezvous and Capture (AR&C) capability[1]. In support of these mission requirements, engineers at NASA's George C. Marshall Space Flight Center (MSFC) have designed and tested an AR&C system which, along with the capability to lower mission operation costs, also has a great deal of safety, redundancy and reliability designed into it. The system incorporates some of the latest innovations in Global Positioning System (GPS) space navigation, laser sensor technologies and automated mission planning algorithms as well as the continuous capability for ground monitoring and intervention. This paper present results from the official system tests performed in MSFC's Flight Robotics Laboratory (FRL) with digital simulations and hardware in the loop tests. The test cases in this paper, which are only a subset of the entire test profile, cover the operating the ranges from 40 km relative separation to dock. The results show that the AR&C system can safely and reliably perform automated rendezvous and docking missions in the absence of system failures. When failures were included the system used its automated collision avoidance logic to recover safely.

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Correspondence to James Lomas: Phone 256-544-8305 email: james.lomas@msfc.nasa.gov

AR&C PROJECT BACKGROUND

The objective of the AR&C project is to advance rendezvous and docking technologies from manual to automated capabilities. This goal is seen as essential for two reasons: to reduce the recurring cost of routine docking missions; and for missions that require automated operations due to long communication delays, (i.e. robotic missions to Mars). To that end, hardware, software, documentation and test facilities were developed to support the design of an AR&C system. Specifically, the project objectives were defined as follows: provide design criteria, procedures and simulation techniques that will influence standardization of AR&C systems; establish test facilities and procedures to support the development and verification of future systems prior to flight; demonstrate relevant technologies for future AR&C systems; establish functional performance capabilities of subsystem elements for an AR&C system; demonstrate spacecraft automated rendezvous, proximity operations, station keeping, capture and collision avoidance maneuvers in a controlled ground simulation and in space; demonstrate the capability to dock with 100 percent success in the absence of system failures; demonstrate the safety of AR&C including recovery from anomalous situations; and contribute to the future capability to conduct robotic spacecraft operations with the ISS and other space platforms[2]. For the purpose of the program, most of these objectives were demonstrated through flight experiments, detailed 6 Degree-of-Freedom (6 DoF) Hardware In The Loop (HITL) simulations and digital tests.

AR&C SYSTEM DESCRIPTION

The AR&C system consists of several components, each of which is necessary in one or more phases of an automated docking mission. Table 1 lists the assumptions made about the Chaser and Target Vehicles during the design and testing process. Figure 1 gives a pictorial overview of the elements included in the AR&C system. On the Chaser Vehicle (CV), an on-board computer performs hardware commanding, telemetry, guidance, navigation and control, collision avoidance maneuvers (CAMs) and system monitoring functions. Long-range absolute and relative navigation is accomplished using a 12 channel, L1, CA code GPS receiver in combination with an Inertial Measurement Unit (IMU). Short-range (100 meters to dock) relative navigation and attitude information is provided by the Video Guidance Sensor (VGS). The Three-Point Docking Mechanism (TPDM) performs the actual physical latching of the two spacecraft. The TV is assumed to be stabilized in attitude and equipped with a set of trunions that align with the TPDM latches, a set of passive reflectors that serve as the VGS target, a 12 channel, L1, CA GPS receiver and a short-range transmitter that sends GPS data to the CV. All of this hardware was integrated together and tested in the MSFC FRL. It is significant to note that the AR&C project has already tested one element of the system in space on two separate occasions. The VGS was flown on STS-87 and STS-95. The purpose of these flight experiments was to verify the operational characteristics of the VGS in the low earth orbit environment and both were "very successful"[3].

The AR&C system mission scenarios include each of the following functions: autonomous phasing and rendezvous with a target spacecraft after the CV's arrival in orbit, automated approach and departure maneuvers and automated "soft dock" with the TV. This system is able to meet all of these requirements without ground intervention while providing real time ground monitoring capability and intervention. The results presented in this paper only cover proximity operations. Automated orbit transfer and rendezvous test results will be presented in a later paper.

Table 1 CHASER AND TARGET VEHICLE ASSUMPTIONS

Chaser Vehicle Assumptions	Target Vehicle Assumptions
One 4,000 LB thrust, main engine, Isp = 260 sec	TV has a passive VGS target mounted on it.
RCS thrust available in each body direction: 45 LB, Isp = 220 sec, Full 6 DoF Control	TV transmitting raw GPS data for CV relative nav
Total CV mass at Arrival in Orbit: 75,000 LB	TV GPS data transmission range : 7 km
Propellant for main engine and RCS: 9,900 LB	TV Orbit: 220 nm, Circular, 51.6° Inclination
CV Payload delivered to TV: 55,000 LB	TV attitude stabilized to ±1° in each axis.

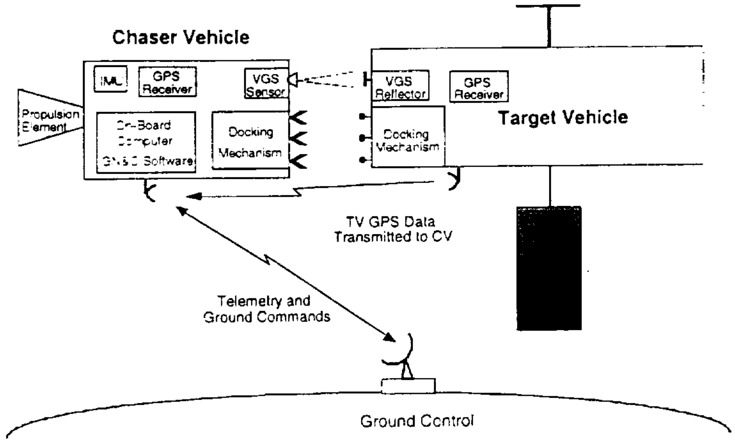
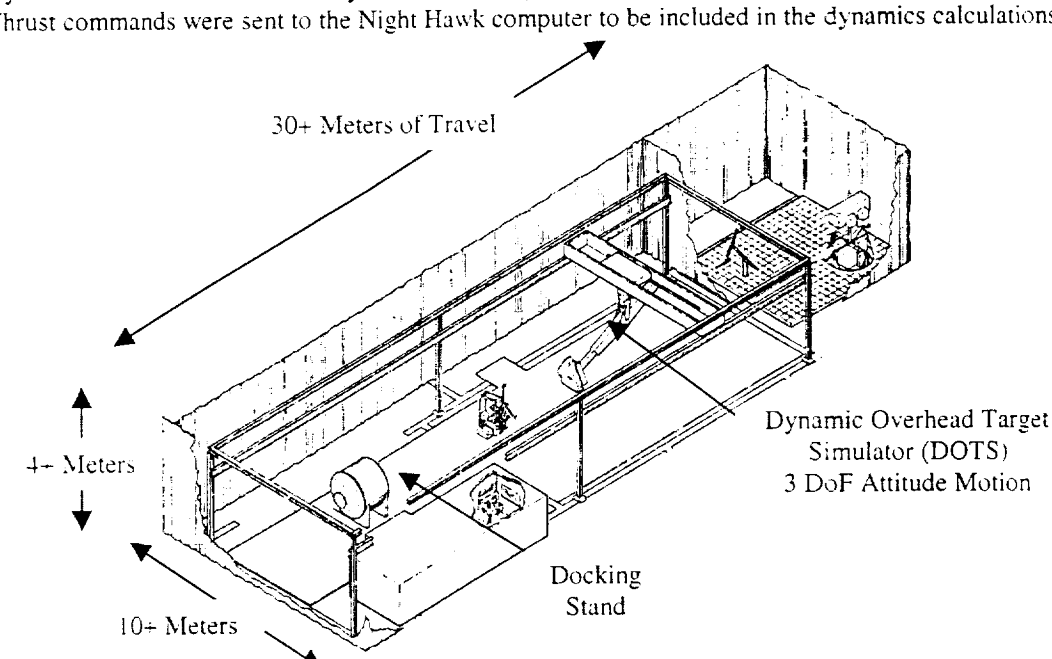


Figure 1 AR&C System Elements

AR&C SYSTEM TEST OVERVIEW

The AR&C tests were performed in the MSFC FRL (see Figure 2). For all test cases, "truth" dynamics were calculated on a Harris Night Hawk which served as the central simulation computer. This computer in-turn stimulated a 20-channel GPS simulator, IMU math model, thruster models as well as all environment models in real time. The 30 m to docking tests were 6 DoF HITL cases using the Dynamic Overhead Target Simulator (DOTS), docking mechanisms, VGS sensor and target hardware. The relative motion of the two vehicles was calculated on the Night Hawk and modeled by moving the DOTS. The DOTS was outfitted with the passive elements of the system (VGS target and docking trunions). Although the DOTS represented the target vehicle, generally thought of as stationary during the approach, it was easier to mount passive elements on the dynamic part of the simulator rather than the active elements which require power and data connections. Due to the large distances in the rendezvous to 30 m cases, the DOTs and VGS hardware were not used. Instead, these were digital tests where the Night Hawk computer drove a functionally equivalent VGS digital model. In all cases, the AR&C flight computer, a Power PC, executed the GN&C software as well as the command, telemetry handling and housekeeping functions. Commands issued by the GN&C were sent to the system elements (GPS receiver, VGS, TPDM) via communications lines. Thrust commands were sent to the Night Hawk computer to be included in the dynamics calculations.



Rendezvous Profile

Figure 2 MSFC Flight Robotics Laboratory

The AR&C system has been tested throughout all phases of a rendezvous mission starting from orbit insertion, through orbit transfer and phasing, proximity operations, docking and also undock and back away. Due to space constraints, this paper only discusses test results concerning proximity operations and dock. Proximity operations for the AR&C system begin with the Chaser in a coelliptic orbit with the Target at a point 40 km behind and 5 km below. A diagram of the nominal motion of the Chaser vehicle relative to the Target is shown in Figures 3 and 4. Included in the test cases are approaches along the +V-Bar, +R-Bar and –R-Bar axes of the target. As shown in Figure 3, +V-Bar and –R-Bar type missions approach the TV from in front (direction of orbital velocity). +R-Bar profiles approach from behind and underneath (nadir direction) the Target vehicle.

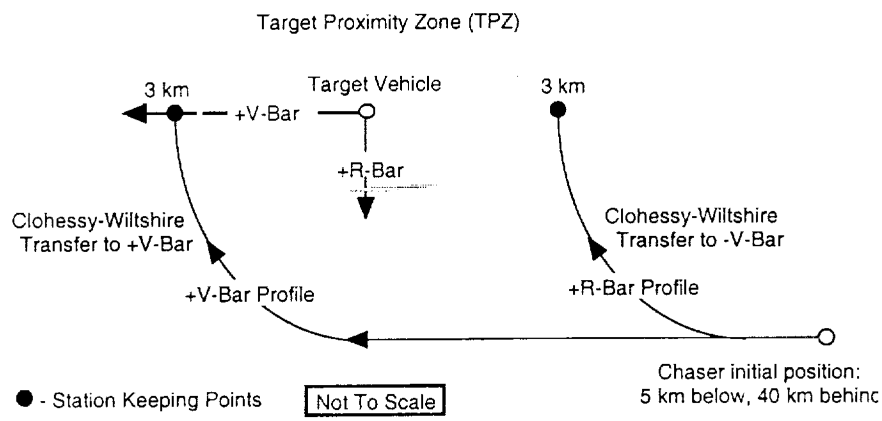


Figure 3 Relative Motion of AR&C Proximity Operations Trajectories

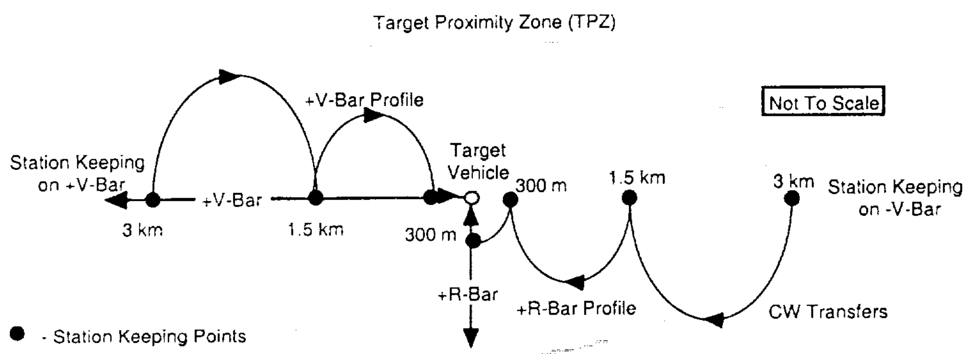


Figure 4 Relative Motion of AR&C Proximity Operations Trajectories

Seven test cases are presented that included nominal approaches as well as commanded aborts and hardware failures that resulted in automatic CAMs. The test cases are listed in Table 2 and are described in detail in the results section.

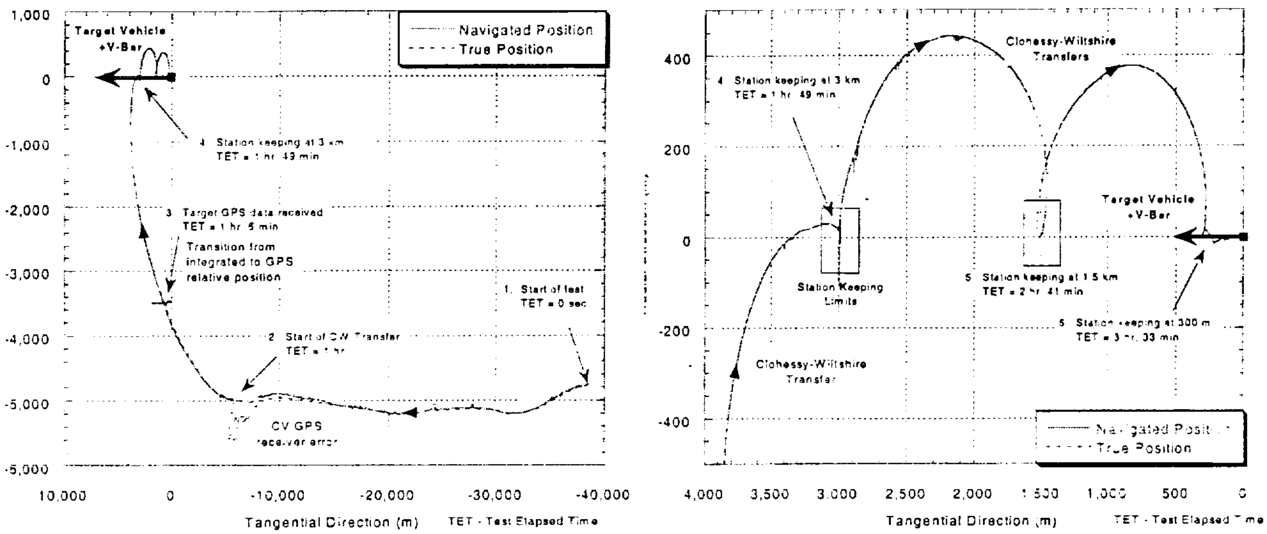
Table 2 AR&C PROXIMITY OPERATIONS TEST CASES

Case Number	Test Cases	Starting Position	Ending Position	Duration (Hr:Min)	Commands Sent	Faults
1	Rendezvous to 30 m, +V-Bar	40 km Behind, 5 km Below	30 m on +V-Bar	4:20	None	None
2	Rendezvous to 30 m, +R-Bar	40 km Behind, 5 km Below	30 m on +R-Bar	4:30	None	None
3	Rendezvous to 30 m, +V-Bar	40 km Behind, 5 km Below	30 m on +V-Bar	5:10	None	Loss of TV GPS Data, Loss of VGS Data
4	Rendezvous to 30 m, –R-Bar	40 km Behind, 5 km Below	30 m on -R-Bar	6:40	TPZ Abort, New Event Sequence	None
5	30 m to Dock, +V-Bar	30 m on +V-Bar	Docked	0:27	None	None
6	30 m to Dock, +R-Bar	30 m on +R-Bar	Docked	0:27	None	None
7	30 m to Dock, +V-Bar	30 m on +V-Bar	Docked	0:41	Wave Off	Loss of VGS Data, TPDM Fault

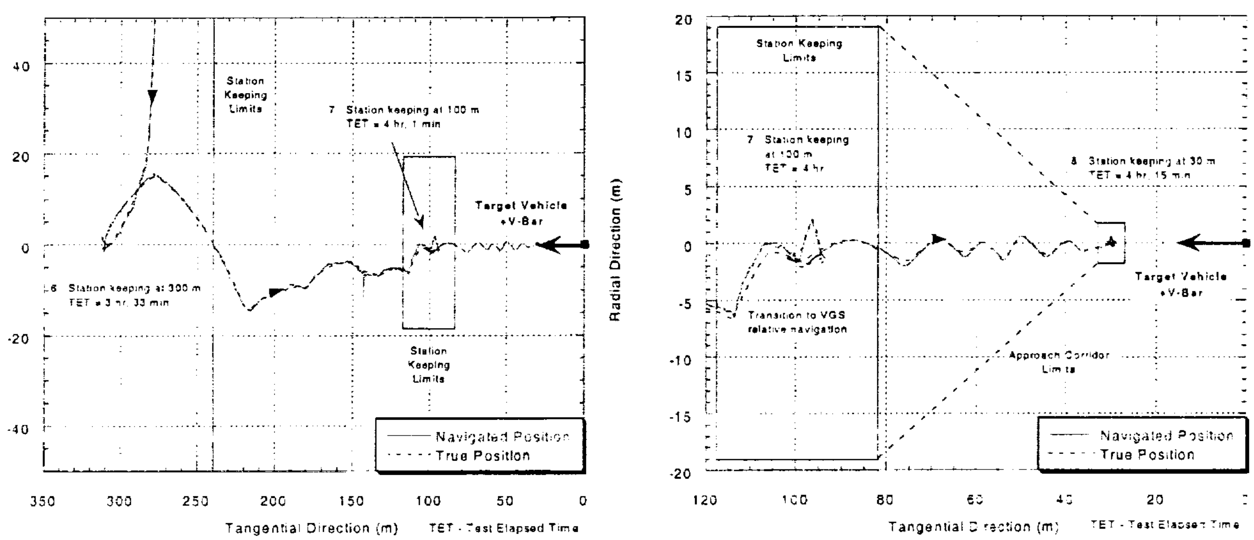
AR&C SYSTEM TEST RESULTS

Test 1: Nominal Rendezvous to 30 m, +V-Bar

The Chaser began at the initial rendezvous point with a relative position of 40 km behind and 5 km below the Target vehicle. The Chaser was in controlled drift mode and used GPS navigation to determine its own state and a propagated state vector for the Target to calculate its relative position. During the entire test, the Chaser's control system maintained a local vertical, local horizontal attitude. The controlled drift lasted for an hour during which time the range between the two vehicles decreased due to the differences in orbital rates. At point 2 in Figure 5, the CV initiated a CW transfer to the 3 km point on the +V-Bar of the Target. Note that just prior to the CW transfer, there is a large deviation between the navigated and true relative position. This was caused by a timing error in the CV GPS receiver tracking loops. This error only lasted for a few minutes but had a dramatic effect on the nav error. At point 3 on Figure 5, the CV entered the broadcast range of the Target's GPS data (assumed to be 7 km). Once within this range the navigation mode switched to using the two vehicles' raw GPS data to determine their relative state. Point 4 on Figure 6 shows the CV entering into a station keeping event 3 km on the +V-Bar. The allowable station keeping limits are illustrated on the relative motion plots and decrease in size as the CV approaches the TV. The size of these station keeping "boxes" were based upon ISS approach requirements. If the CV were to go outside of these "boxes", an automatic CAM would be triggered, causing the CV to retreat to the previous station keeping point. Points 5 and 6 on Figure 6 show CW transfers to the 1.5 km and 300 m points. Inside of 300 m, the CV used straight line, forced motion transfers to approach the TV. This method and the approach corridor limits were also based upon ISS requirements. From 300 m, the CV approaches to the 100 m point on the +V-Bar and transitions to using the VGS as its primary navigation sensor. The VGS has an approximate maximum tracking range of 150 m and experience has shown while approaching the TV, transitioning from relative GPS to VGS is best accomplished when the CV is station keeping. Figure 7 shows the CV's approach to 100 m with good agreement between the navigated and true states. Figure 8 shows the 100 m station keeping event as well as the transition to VGS nav. After the station keeping event, the CV approached to the 30 m point along the +V-Bar and entered a final station keeping.



Figures 5 & 6 Test 1 Relative Motion Plots



Figures 7 & 8 Test 1 Relative Motion Plots

Table 3 lists the navigation error statistics for portion of the mission that used relative GPS (40 km to 100 m). Table 4 shows the error statistics while the VGS was used as the primary navigation sensor (100 m to 30 m). Its point of maximum error occurred during the 100 m station keeping event and steadily decreased with range. This is illustrated in Figure 8. Table 5 gives the duration, amount of propellant used and the calculated delta velocity (Delta-V) for each event and the totals.

Table 3 TEST 1 RELATIVE POSITION ERROR USING GPS

	Radial Position Error (m)	Tangential Position Error (m)	Normal Position Error (m)
|Maximum|	108.65	10.90	1.52
Mean	-0.80	0.16	0.07
Std Deviation	3.69	1.43	0.37

Table 4 TEST 1 RELATIVE POSITION ERROR USING VGS (100 m to 30 m)

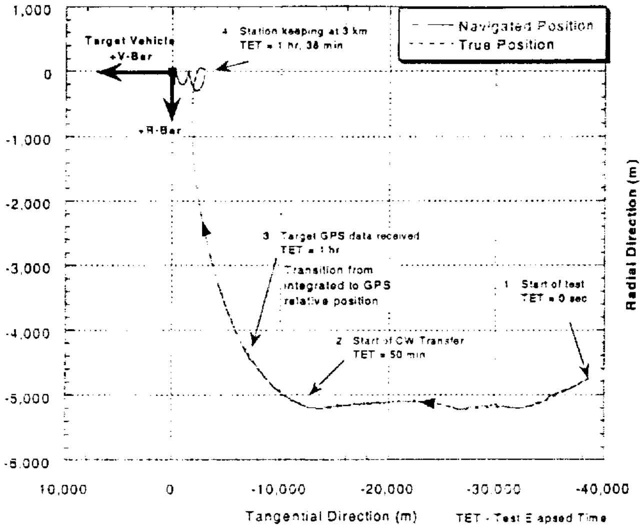
	Radial Position Error (cm)	Tangential Position Error (cm)	Normal Position Error (cm)
Maximum	110	142	110
Mean	-11	21	-24
Std Deviation	30	33	28

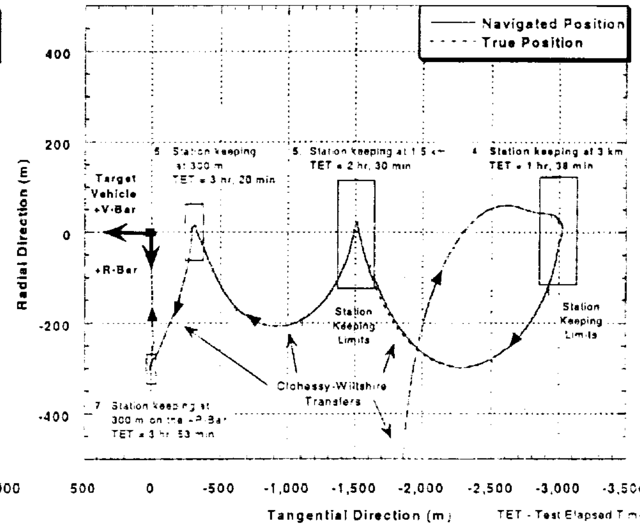
Table 5 TEST 1 TIME, PROPELLANT AND DELTA-V BUDGET

Event	Duration (min)	Delta Mass (kg)	Delta-V (m/s)
Controlled Drift	60.9	122.95	8.18
CW Transfer to 3 km	48.78	117.76	7.88
SK at 3 km	5	2.99	0.21
CW Transfer to 1.5 km	46.5	41.25	2.76
SK at 1.5 km	5	9.33	0.64
CW transfer to 300 m	46.73	26.64	1.79
SK at 300 m	5	14.22	0.96
Approach to 100 m	23.75	18.35	1.23
SK at 100 m	5	8.70	0.58
Approach to 30 m	9	35.18	2.36
SK at 30 m	5	13.33	0.90
Totals	**4 hrs, 20 min**	**410.70 kg**	**27.49 m/s**

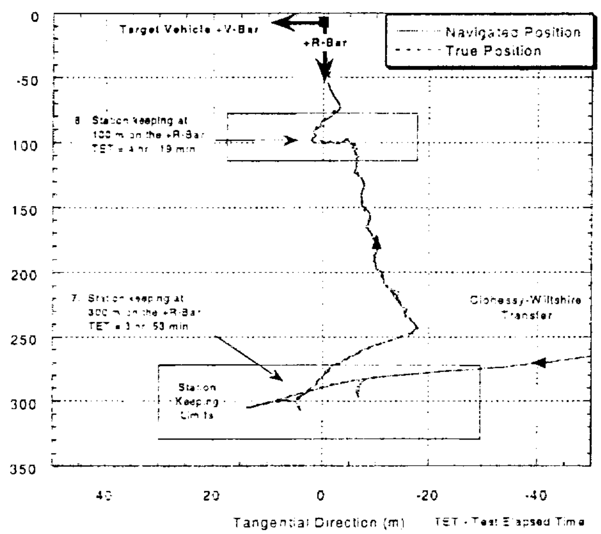
Test 2: Nominal Rendezvous to 30 m, +R-Bar

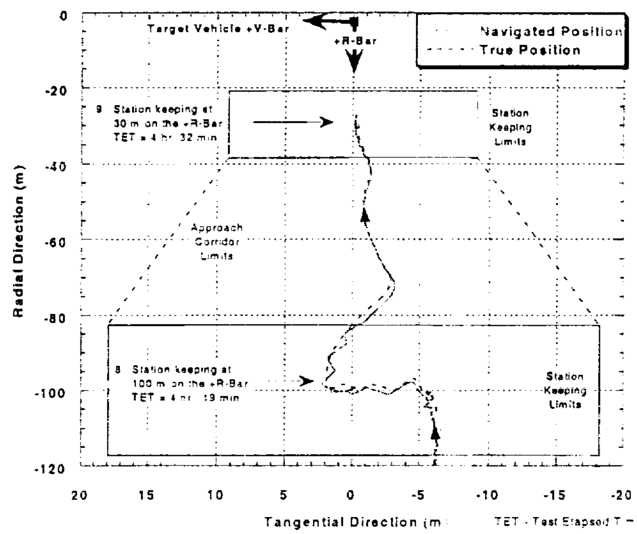
Test 2 began with identical initial conditions as Test 1 and the on-board computer was loaded with a +R-Bar approach sequence. The primary difference between the +V-Bar and +R-Bar profiles is that for the latter, the CV approaches along the –V-Bar before transferring to the +R-Bar axis. The reason for this is to allow the CV to have stable station keeping points during the approach. Station keeping points on the ± R-Bar are not stable because to maintain a relative position to the Target, the Chaser must continuously thrust in the direction of orbital velocity to null the difference in mean orbital rates. The Chaser began in controlled drift mode then executed a CW transfer to 3 km on the -V-Bar of the Target. Calculated relative navigation was used until the CV came within 7 km of the Target and then switched to relative GPS shown at point 3 in Figure 9. Upon reaching the 3 km point on the –V-Bar, the CV station kept for a short time. This was followed by two more CW transfers and two station keeping events at 1.5 km and 300 m (see Figure 10). After finishing the station keeping event at 300 m on the –V-Bar, the CV transferred to 300 m point on the +R-Bar (see point 7 in Figure 10). It then and continued its approach to the 100 m point. At 100 m, the Chaser switched to VGS relative navigation and approached along the +R-Bar to 30 m. The test successfully concluded with the Chaser at the 30 m point on the +R-Bar (see point 9 in Figure 12). Tables 6 and 7 list the navigation error statistics for the relative GPS and VGS portions of the mission. Again note that the largest VGS errors occurred during the 100 m station keeping event on +R-Bar (see Figure 12). Table 8 gives the duration, propellant used and Delta-V for each event and the totals. One interesting point to notice is the fuel required for the controlled drift portion of test 1 versus test 2. Although the two drift distances were essentially the same, test 1 used almost twice as much propellant. The reason lies in the fact that during test 1, there was a GPS receiver timing error which caused the relative state to be in error thereby causing the guidance to command a large radial (upward) thrust. Since this timing error did not happen in test 2, the navigated relative position stayed very close to the true position and no extraneous thrust commands were sent.





Figures 9 & 10: Test 2 Relative Motion Plots





Figures 11 & 12 Test 2 Relative Motion Plots

Table 6 TEST 2 RELATIVE POSITION ERROR USING GPS

	Radial Position Error (m)	Tangential Position Error (m)	Normal Position Error (m)
|Maximum|	20.49	17.3	2.42
Mean	0.55	-0.21	0.10
Std Deviation	1.79	1.18	0.41

Table 7 TEST 2 RELATIVE POSITION ERROR USING VGS (100 m to 30 m)

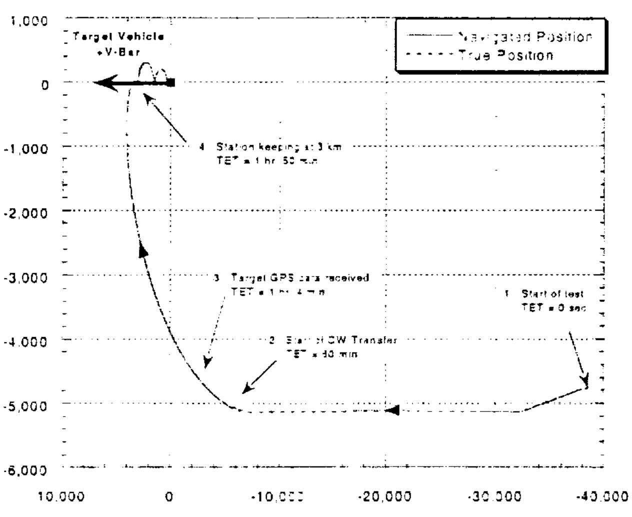
	Radial Position Error (cm)	Tangential Position Error (cm)	Normal Position Error (cm)
|Maximum|	223	97	19
Mean	-124	-2	5
Std Deviation	32	28	8

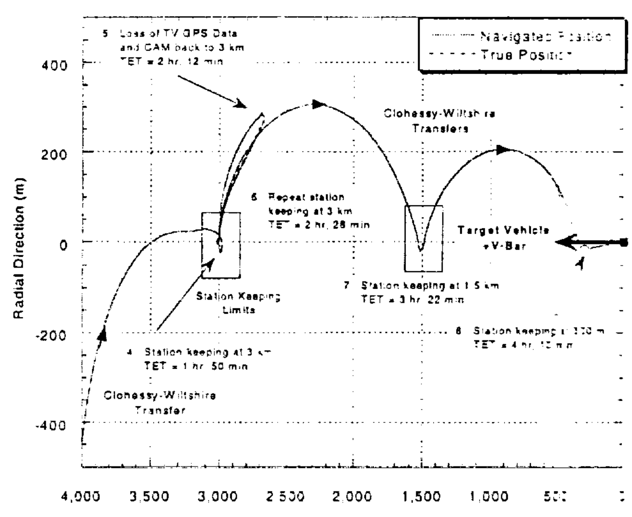
Table 8 TEST 2 TIME, PROPELLANT AND DELTA-V BUDGET

Event	Duration (min)	Delta Mass (kg)	Delta-V (m/s)
Controlled Drift	49.57	63.05	4.19
CW to 3 km -Vbar	49	127.56	8.51
3 km SK	5	4.03	0.28
CW to 1.5 km -Vbar	46.67	35.46	2.37
1.5 km SK	5	3.21	0.22
CW to 300 m -Vbar	46.43	34.60	2.32
300 m SK	5	6.44	0.44
CW to 300 m +Rbar	26.18	33.52	2.25
300 m SK	5	16.70	1.13
Approach to 100 m +Rbar	20.85	25.85	1.74
100 m SK	5	10.30	0.69
Approach to 30 m +Rbar	7.92	9.98	0.67
30 m SK	5	10.23	0.69
Totals	**4 hrs, 30 min**	**380.93 kg**	**25.50 m/s**

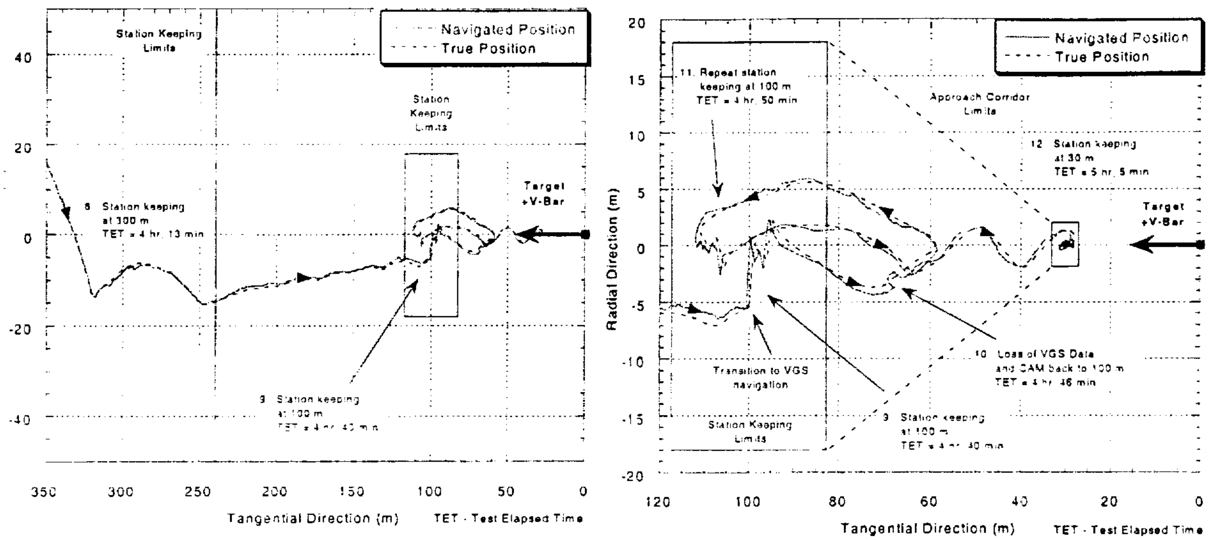
Test 3: Rendezvous to 30 m, +V-Bar with GPS and VGS Faults

This test was identical to Test 1 except for induced faults. The first occurred when the Chaser was approaching from 3 km to 1.5 km. During this phase of the mission, the CV was using relative GPS navigation supplied by its GPS receiver as well as the Target's raw GPS data. The fault involved disrupting the data link from the Target for 5 seconds. This did not cause a CAM, as the AR&C flight rules allow for up to a 30 second loss of relative GPS data in this phase of the mission. Then the TV GPS signal was cut completely and the CV performed an automatic CAM back to the 3 km point on the +V-Bar (point 5, Figure 14). At 3 km, the Target GPS signal was reestablished and the Chaser continued its approach to 100 m on the +V-Bar. The Chaser then used the VGS to continue its approach to 30 m. The third fault was induced by disrupting VGS data for 5 seconds when the chaser was between 70 and 80 m from the target. This short outage did not cause the Chaser to CAM. The VGS data was then terminated, causing the CV to CAM back to the 100 m point (point 10, Figure 16). When the Chaser arrived back at the 100 m point, VGS data was restored and the test concluded with the Chaser at the 30 m point on the +V-Bar. Tables 9 and 10 list the navigation error statistics for the relative GPS and VGS portions of the mission. Table 11 gives the duration, propellant used and Delta-V for each event and the totals. The total propellant required for this test was essentially the same as test 1. This was because although the GPS timing error did not occur in the controlled drift, a significant amount of fuel was required to execute the CAM back to the 3 km point.





Figures 13 & 14 Test 3 Relative Motion Plots



Figures 15 & 16 Test 3 Relative Motion Plots

Table 9 TEST 3 RELATIVE POSITION ERROR USING GPS

	Radial Position Error (m)	Tangential Position Error (m)	Normal Position Error (m)
|Maximum|	7.23	13.80	2.80
Mean	-0.33	0.01	0.03
Std Deviation	1.36	0.76	0.40

Table 10 TEST 3 RELATIVE POSITION ERROR USING VGS (100 m to 30 m)

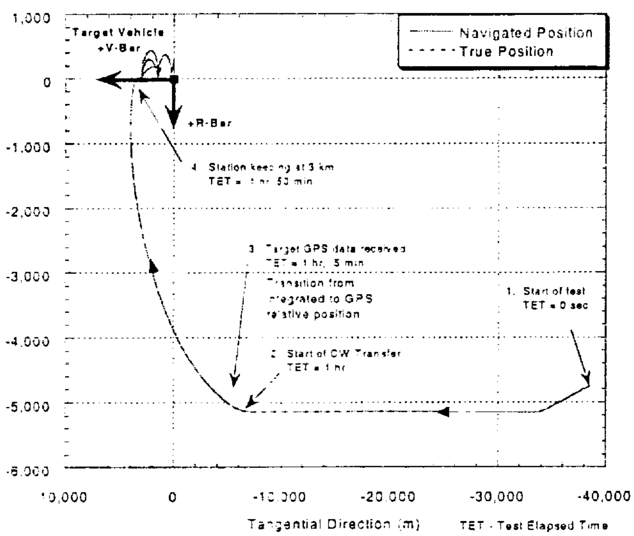
	Radial Position Error (cm)	Tangential Position Error (cm)	Normal Position Error (cm)
|Maximum|	115	198	116
Mean	-15	113	-27
Std Deviation	34	25	33

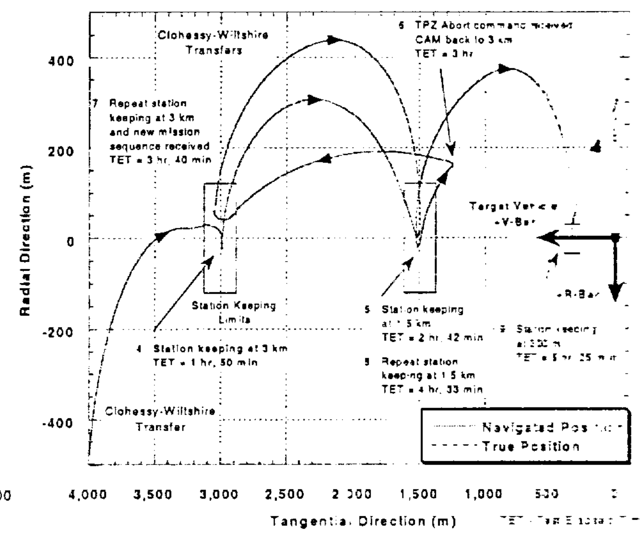
Table 11 TEST 3 TIME, PROPELLANT AND DELTA-V BUDGET

Event	Duration (min)	Delta Mass (kg)	Delta-V (m/s)
Free Drift	61.72	61.90	4.11
CW to 3 km +Vbar	48.95	89.12	5.94
3 km SK	5.02	4.15	0.28
CW to 1.5 km/CAM	34.92	86.05	5.75
3 km SK	5.02	6.19	0.43
CW to 1.5 km	46.60	31.28	2.09
1.5 km SK	5.02	3.63	0.22
CW to 300 m +Vbar	46.30	28.65	1.92
300 m SK	5.02	3.63	0.25
Approach to 100 m +Vbar	20.60	15.42	1.04
100 m SK	5.02	10.12	0.68
Approach to 30 m/CAM	6.58	20.38	1.37
100 m SK	5.02	14.19	0.95
Approach to 30 m +Vbar	9.62	16.93	1.14
30 m SK	5.02	18.80	1.27
Totals	**5 hrs, 10 min**	**410.44 kg**	**27.44 m/s**

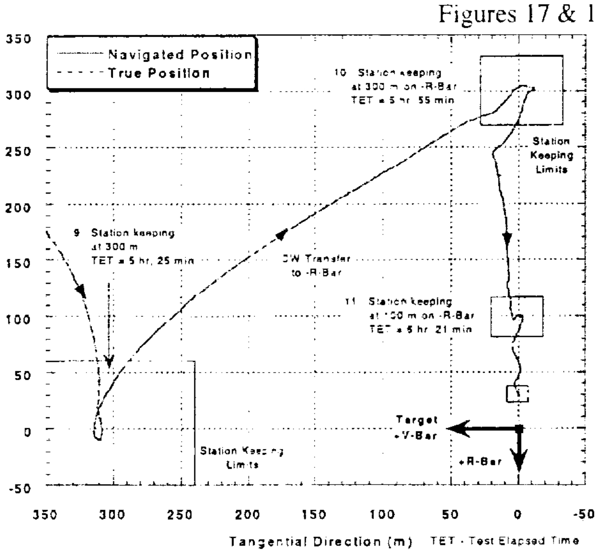
Test 4: Rendezvous to 30 m, -R-Bar with TPZ Abort and New Sequence Command

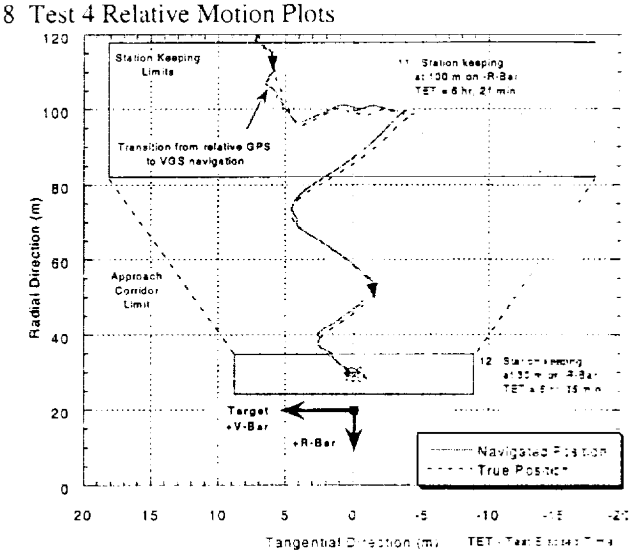
This test was identical to test 1 except that during the mission two non-standard commands were issued. This test began at the initial rendezvous point (40 km behind and 5 km below the Target) and the mission progressed nominally until the Chaser was approaching from 1.5 km to 300 m. At this point, a TPZ Abort command was issued from the command console which caused the CV to retreat immediately to 3 km (point 6, Figure 18). Upon arriving at the 3 km point, the Chaser entered station keeping and waited for further instructions. Then a new mission sequence was sent to the Chaser that changed the approach type from +V-Bar to -R-Bar. This new approach is similar to the +V-Bar however at the 300 m position on the +V-Bar the CV executed a CW transfer to the 300 m point on the -R-Bar. From there, the Chaser approached along the -R-Bar to the 100 m point (with 5 minute station keeping events at 300 m and 100 m). At the 100 m point, the Chaser transitioned to the VGS navigation mode (point 11, Figure 20) and approached to the 30 m point. The test concluded with the Chaser vehicle at 30 m on the -R-Bar. Tables 12 and 13 list the navigation error statistics for the relative GPS and VGS portions of the mission. Table 14 gives the duration, propellant used and Delta-V for each event and the totals. From this table its easy to see that the TPZ abort maneuver is very expensive in terms of propellant. This maneuver took approximately 146 kg of propellant as opposed to only 26 kg for the nominal CW transfer.





Figures 17 & 18 Test 4 Relative Motion Plots





Figures 19 & 20 Test 4 Relative Motion Plots

Table 12 TEST 4 RELATIVE POSITION ERROR USING GPS

	Radial Position Error (m)	Tangential Position Error (m)	Normal Position Error (m)
|Maximum|	9.85	30.84	3.65
Mean	-0.05	-0.02	0.04
Std Deviation	0.60	1.09	0.38

Table 13 TEST 4 RELATIVE POSITION ERROR USING VGS (100 m to 30 m)

	Radial Position Error (m)	Tangential Position Error (m)	Normal Position Error (m)
|Maximum|	2.08	1.08	0.42
Mean	1.12	0.18	0.31
Std Deviation	0.22	0.31	0.05

Table 14 TEST 4 TIME, PROPELLANT AND DELTA-V BUDGET

Event	**Duration (min)**	**Delta Mass (kg)**	**Delta-V (m/s)**
Free Drift	61.77	60.92	4.05
CW to 3 km	48.65	89.23	5.96
3 km SK	5.02	4.98	0.34
CW to 1.5 km	46.57	33.15	2.21
1.5 km SK	5.02	3.50	0.24
CW to 300 m/TPZ ABORT	53.80	146.46	9.81
3 km SK	5.03	0.37	0.03
CW to 1.5 km	47.05	25.42	1.71
1.5 km SK	5.02	1.93	0.14
CW to 300 m +Vbar	46.95	21.46	1.44
300 m SK	5.02	2.14	0.15
CW to 300 m -Rbar	25.47	25.88	1.74
300 m SK	5.02	15.02	1.02
Approach to 100 m -Rbar	21.20	29.94	2.02
100 m SK	5.02	12.29	0.83
Approach to 30 m -Rbar	8.40	14.90	1.00
30 m SK	5.02	19.60	1.32
Totals	**6 hrs, 40 min**	**507.19 kg**	**34.01 m/s**

Test 5: Nominal 30 m to Dock, +V-Bar

This was a HITL test and used the DOTS overhead crane, VGS and TPDM hardware. It began with the Chaser 30 m away from the Target vehicle on its +V-Bar. The Chaser started in a station keeping mode and after acquiring lock with the VGS, performed a forced motion approach along the +V-Bar to the 10 m point (point 2, Figure 21). After another station keeping event at the 10 m point, the Chaser transitioned to terminal autopilot mode and proceeded in to dock. The test concluded with the TPDM hardware achieving dock and the Chaser entering standby mode. Figure 21 shows the navigated and true relative motion profile for the test. Tables 15 and 16 give the relative error statistics for the run and the final error at dock. These errors show a very good agreement between the navigated and true relative states.

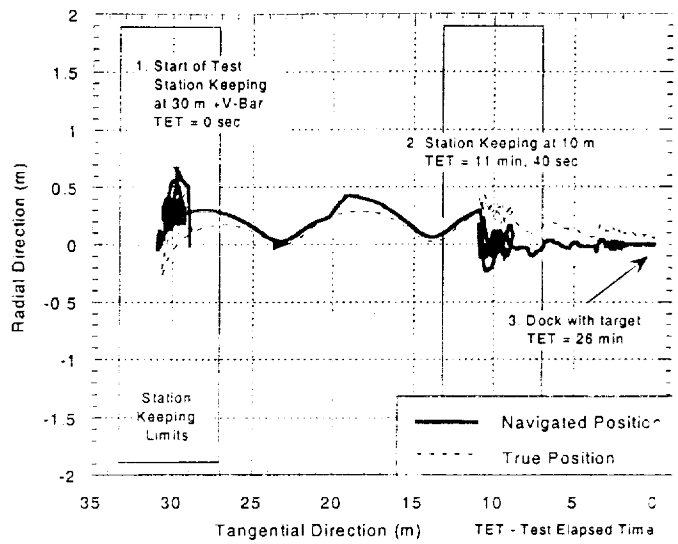


Figure 21 Test 5 Relative Motion Plot

Table 15 TEST 5 RELATIVE POSITION ERROR USING VGS

	Radial Error (cm)	Tangential Error (cm)	Normal Error (cm)
| Maximum |	53	63	26
Mean	-6	20	-5
Std Deviation	17	18	13

Table 16 TEST 5 NAVIGATED POSITION ERROR AT DOCK

Radial Error (cm)	Tangential Error (cm)	Normal Error (cm)
5	3	9

Test 6: Nominal 30 m to Dock, +R-Bar

This was also a HITL test that used the DOTS. As before, it began with the Chaser 30 m away from the Target along its +R-Bar. The Chaser started in a station keeping event and after locking on with the VGS, performed a forced approach along the +R-Bar to the 10 m point (point 2, Figure 22). After another station keeping event, the Chaser transitioned to terminal autopilot mode and proceeded in to dock. During the final approach, the VGS lost lock on the target for 6 seconds (point 3, Figure 22). During that time you can see the relative state jumped approximately 2 meters as the state changed from that of the VGS to that of the GPS filter. Had the dropout lasted 4 more seconds, an automatic CAM would have been triggered and the CV would have retreated back to the 10 m point. However the VGS locked back on to the target and the approach continued. The test concluded with the TPDM hardware achieving dock and the CV entering standby mode. Figure 22 shows the navigated and true relative motion profile for the test. Tables 17 and 18 give the relative error statistics for the run and the final error at dock. The maximum error values in Table 17 represent the jump in state when the VGS lost lock. An obvious improvement to the system would be to filter the VGS and GPS states to avoid this type of behavior.

Table 17 TEST 6 RELATIVE POSITION ERROR

	Radial Error (cm)	Tangential Error (cm)	Normal Error (cm)
| Maximum |	365	48	41
Mean	-18	8	9
Std Deviation	22	19	19

Table 18 TEST 6 NAVIGATED POSITION ERROR AT DOCK

Radial Error (cm)	Tangential Error (cm)	Normal Error (cm)
-2	-5	0.5

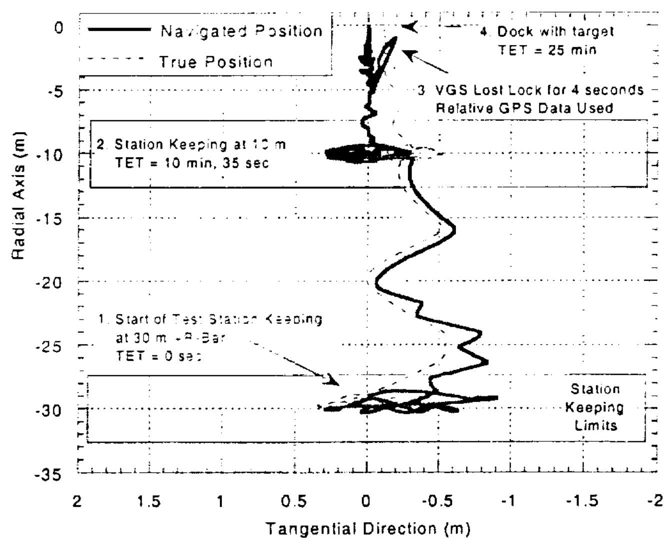


Figure 22 Test 6 Relative Motion Plot

Test 7: 30 m to Dock, +V-Bar with Wave Off Command and VGS, TPDM Faults

This final case was also a HIWL test that used the DOTS in the FRL. It began with the same initial conditions as test 5 which had the Chaser station keeping at the 30 m point on the +V-Bar of the Target vehicle. After locking on with the VGS, the CV performed a forced approach along the V-Bar to the 10 m point and started station keeping. At the end of the station keeping event, the CV transitioned to terminal autopilot mode and started its final approach to dock. However when the Chaser was between 10 and 6 m away from the target, a planned VGS fault was introduced which stopped the VGS data to the OBC for 3 seconds (point 3, Figure 23). This did not cause a CAM as the AR&C flight rules state that the system can handle a loss of VGS data in this range for up to 10 seconds without issuing a CAM. A second fault was then introduced which gave a TPDM "bad" status to the flight comptuer. This fault caused the CV to CAM back to the 10 m point and station keep until the fault was resolved (point 4, Figure 23). When the chaser achieved station keeping at 10 m, a TPDM "good" status indication was restored and after station keeping for 5 minutes, the chaser again approached to dock. At the 5 m point, a Wave Off command was issued from the simulation control console which again caused the chaser to CAM back to the 10 m point and station keep (point 5, Figure 23). After this has been verified, the test concluded with Chaser docking with the Target and entering standby mode.

Table 19 TEST 7 RELATIVE POSITION ERROR

	Radial Error (cm)	Tangential Error (cm)	Normal Error (cm)
|Maximum|	81	58	69
Mean	-28	13	5
Std Deviation	28	17	27

Table 20 TEST 7 NAVIGATED POSITION ERROR AT DOCK

Radial Error (cm)	Tangential Error (cm)	Normal Error (cm)
-8	5	-3

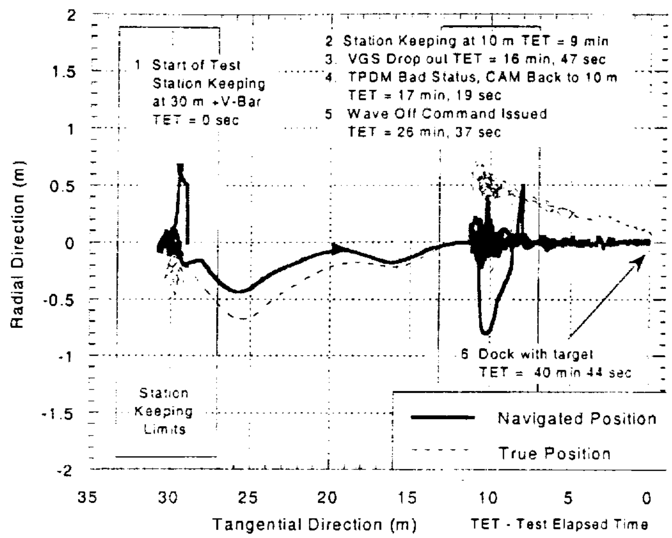


Figure 23 Test 7 Relative Motion Plot

CONCLUSION

The results presented in this paper show that the current AR&C system is able to achieve dock with an cooperative target vehicle 100% of the time in the absence of failures. When failures were introduced, the system's CAM logic automatically detected the anomaly and acted to ensure the safety of the two vehicles while trying to preserve the possibility of mission success. The next step in implementing the AR&C system is to analyze these results further and make any necessary improvements to the system then identify a vehicle or vehicles that could benefit from this technology and test the system for their specific requirements. To this end, the joint NASA-Boeing X-37 Pathfinder program plans to use the AR&C system in a rendezvous and close approach experiment on its second flight in 2003. Once the X-37 flight test hopes to prove that by designing a safe and robust automated system, recurring mission operations costs can be reduced by decreasing the number of ground personnel required for the extensive mission design, preflight planning and training typically required for rendezvous and docking missions.

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